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Laser-Assisted Hybrid Micromachining Processes and Its Applications

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Abstract

Multifunctional properties of miniatures within limited space attract the attention of advanced industries to meet the current and futuristic demands. The fabrication of miniatures at micro/nanoscale is challenging for traditional processes because of size constraint and tool hardness more than workpiece. In existing nontraditional processes, laser is one of versatile shaping process that uses for fabrication of miniatures at micron and submicron scales with precise surface quality due to highly flexible nature with application of short and ultrafast lasers. Such lasers are broadly used in microfabrication of electrical, mechanical, and photonic devices for surface structuring. Even though, laser machining suffers with several drawbacks like spattering, burr formation, recast layer, and thermal stresses. Instead of this, dimensional control and straight cut profiles become challenging. To overcome these problems, laser is hybridized with other processes (traditional/nontraditional) referred as laser-assisted hybrid processes. Generally, performances of hybrid processes are better than the individual one at similar conditions. In present chapter, the various laser-based hybridized processes are discussed with their applicability for shaping of materials at micron/submicron level. Here, laser is considered as energy source and their hybridization with other processes is presented with name of laser-assisted hybrid micromachining processes (LA-HMMPs). Instead of this, the present chapter covers the different types of LA-HMMPs and their basic mechanism of material removal with suitability for microfabrication in such a way that it becomes easier for readers.

***Keywords*:** Arc, machining, laser, hybrid, EDM, ECM, ECSM, grinding

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7.1 Introduction

Laser (light amplification by stimulated emission of radiation) is an electromagnetic radiation that uses in various fields of manufacturing, like cutting, welding, forming, sintering, heat treatment, and surface coating. It has several unique features like monochromic (same wavelength), coherent (same phase), focus in small wavelength ranges (0.50–70 μm), and high-power intensity (in order to 1 MW/cm^2) [1–3]. It shows their ability to travel long distance without scattering and also focuses in very small and narrow area, as well as inaccessible location with application of focusing lens [3, 4]. The key element of laser is photons that responsible for heat generation to make laser for practice applications. Instead of this, the flexible nature of laser with low heat input and high lateral resolution makes it a superior process for fabrication of objects at micron and submicron scales.

In laser beam machining (LBM), the beam of laser is used as heat source, which is generated by stimulated emission of photons. Mostly, flash lamp, reflective mirrors, and laser source are required for generation of laser (Figure 7.1). In LBM, the laser source/medium becomes important parameter for laser light generation. Generally, solid, liquid, gas, or fiber lasers are used as laser medium. In solid laser, the ruby is the first solid laser that used in different industrial applications. Instead of this, neodymium doped yttrium-aluminium-garnet (Nd-YAG), neodymium doped glass (Nd-glass) and neodymium doped yttrium lithium fluoride (Nd-YLF) are also used as solid laser for industrial applications [2, 3, 5]. Fiber lasers are also one type of solid laser where optics fiber especially fiber glass, which is used as laser medium. The carbon dioxide (CO_2), carbon monoxide (CO),

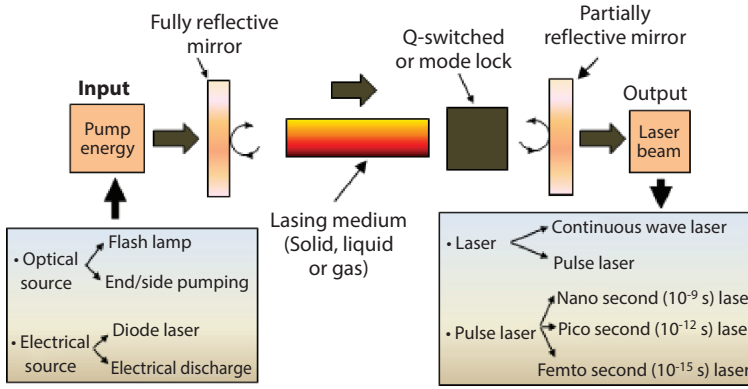

Figure 7.1 Laser generation system.

nitrogen, hydrogen, argon, and excimer lasers are common example of gaseous lasers [1–3], while liquid die is considered as laser medium for liquid laser [2]. Based on the pulse, the laser may be millisecond (ms), microsecond (μs), nanosecond (ns), picosecond (ps), and femtosecond (fs). Generally, long pulse (ms and μs) lasers are used for macromanufacturing, like cutting, drilling, milling, and welding applications, while short pulse (ns) laser and ultrashort pulse (ps/fs) lasers are applied for micromachining and microfabrication.

In simple, the melting and vaporization play important roles in material removal when laser beam has been focused on workpiece surface. In case of micromachining, the laser ablation is responsible for material removal, which can be defined as removal of material from workpiece by pulse laser [3, 5]. In Figure 7.2, a typical laser ablation is presented for a pulse laser [5]. Due to ablation, high heat is generated because of conversion of laser energy into heat energy causes melting and subsequently vaporization of metal from work surface. Such phenomena are completed in different phases, such as heating, melting, vaporization, and ablation (Figure 7.3).

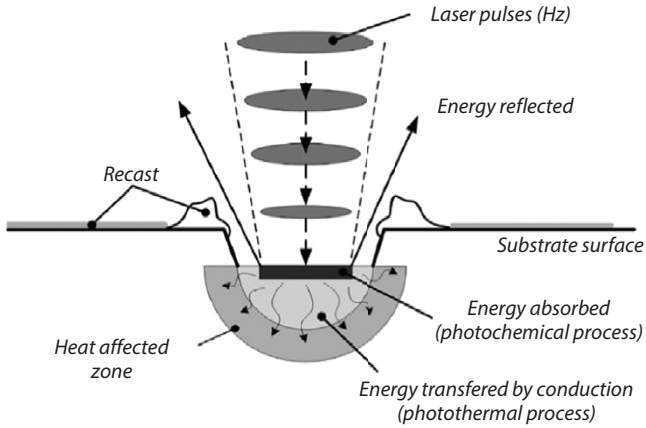

Figure 7.2 Laser ablation phenomena [5].

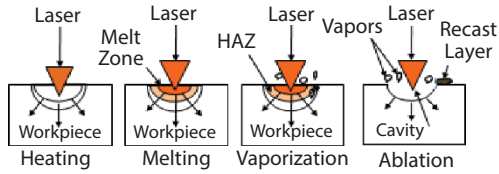

Figure 7.3 Various phases of laser ablation.

In laser beam micromachining (LBMM), the rate of energy deposition is much smaller than the energy transfer time and electron-photon coupling time as which no collateral damages occur [3]. Due to this, negligible heat-affected zone (HAZ) during micromachining by laser radiation, which makes it suitable for processing of materials at micron and submicron scales.

In LBMM, a variety of parameters (controllable/uncontrollable) are significantly affected the performances of material processing at micro and nanoscales. The controllable parameters are covered as laser parameters (wavelength, pulse frequency, and width,), material parameters (thickness and properties), beam parameters (power source, beam diameter, focal length, standoff distance), and other parameters (interaction time, spot diameter, focal spot length). On other hand, the humidity, temperature, work environment, operator skill and machine efficiency are also affected the performances of process. These parameters are come in category of uncontrollable because of challenges in controlling. The various controlled parameters related the LBMM are graphically presented in Figure 7.4, while Table 7.1 presents the effect of control factors on responses.

Off course, laser is wonderful tool for microfabrication with application of short and ultrashort pulse lasers [3]. Due to their unique characteristics, laser can be employed to machine all materials including extremely hard like diamond, ceramic, sapphire to soft like polymers [3, 6–8]. It is

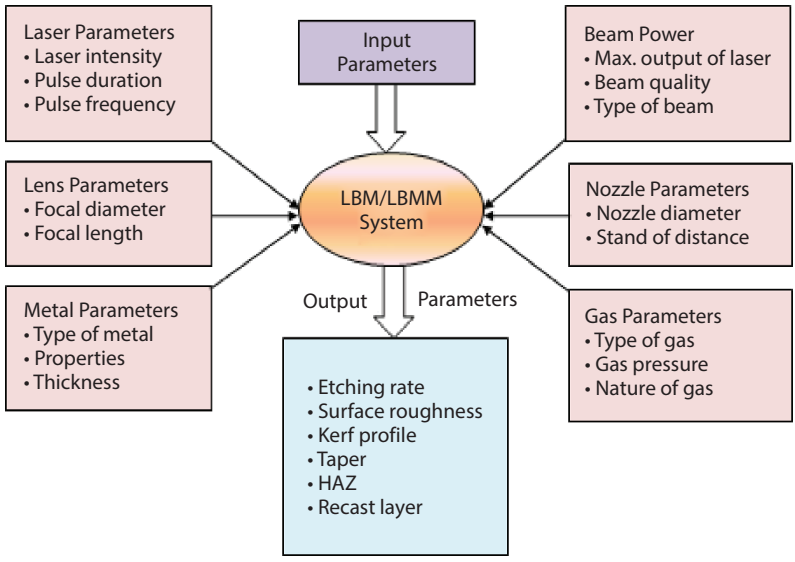

Figure 7.4 Process and performance parameters of LBMM.

Table 7.1 Process parameters and their effects.

Sl. no.	Process parameters	Effects
1	Pulse intensity	Penetration depth, crater profile
2	Pulse width	Ablation rate, crater profile, HAZ
3	Pulse interval	Ejection rate, SQ, recast layer
4	Beam power	Ablation, HAZ, crater geometry
5	Pulse frequency	Penetration depth, SQ, ablation, feature size
6	Gas pressure	Ejection, recast layer, SQ
7	Focal length	Ablation rate, feature size
8	Nozzle distance	Ejection rate, profile of cut
9	Beam profile	Feature shape, informality in micromachining
10	Material thickness	Taper, kerf profile, feature at exit and entry

effectively applied for manufacturing of microelectromechanical (MEM) devices for biomedical, robotics, sensor, actuators, electronics, and computer applications. It also shows their potential in fabrication of microfluidic channels and tubes for drugs supply system. It is significantly used for manufacturing of biomedical implantable items especially cardiovascular stent for medical applications [9].

The applications of laser in micromachining significantly meet the demand of advanced industries but it suffers with several inherent problems like taper profile and uneven diameter at entry and exit of holes. The basic reason behind this is to divergence and convergence nature of beam. Due to this, the straight profiles of laser-drilled holes are difficult to achieve. Such phenomenon needs secondary operation to get the straight and parallel profile of drilled holes as which enhancement in cost and time. Instead of this, high-aspect ratio holes drilling and recast layer formation also limits the applicability of laser for microprocessing of materials. To overcome these problems, laser has been combined with other processes to enhance the machinability and reduce the deficiency of LBMM process. In case of combined processes, the laser mostly assists the performance of combined processes by thermal heating during machining. Such combined process is known as laser-assisted hybrid micromachining processes (LA-HMMPs).

7.2 Laser-Assisted Hybrid Micromachining

Hybrid micromachining processes (HMMPs) can be defined as combination of two or more machining processes in such a way that they utilize their merits and simultaneously minimize/eliminate the demerits of constituent processes to achieve micromachining by removal of material at micron level. On other hands, HMMPs can be defined as an enhanced micromachining processes that aim to achieve the significantly better machining effect by combining at least two different forms of energies like mechanical, thermal, chemical, electrochemical, magnetic, or electromagnetic. Based on involvement, the HMPs (hybrid machining processes) are categorized in two categories as associated HMPs and assisted HMPs [10, 11]. In associated-HMPs, all integrated processes are involved in machining to enhance the performance of process. On other hand, one process involves in machining while other either assists/facilitates the machining or material removal in case of assisted HMPs. The main objectives of HMPs are to exploit the merits and simultaneous eliminate/minimize the demerits of constituent processes. The HMPs significantly enhance the material removal and SQ with reduction in tool wears and specific energy consumption [10–14].

In simple, LA-HMMPs can be defined as combination of LBMM with other (traditional/nontraditional) processes to enhance machinability with combined effort of integrated processes. On other way, LA-HMMPs can be defined as integration of various shaping processes with LBM/LBMM that aim to achieve significantly better machining effects by utilizing at least one or more forms of energies like chemical, electrochemical, thermal, magnetic or mechanical. The main objectives of LA-HMMPs are to utilize the merits with simultaneous eliminate/minimize the demerits of individual process during machining. The major benefits of LA-HMMPs are as higher productivity and machining rate with better SQ, negligible recast layer and lesser cracks formation.

Generally, laser is assisting in nature with integrated machining processes and referred as LA-HMMPs, which are developed with combination of LBM/LBMM with either traditional or nontraditional processes. Hence, LA-HMMPs can be categorized as laser-assisted traditional-HMMPs and laser-assisted nontraditional-HMMPs as presented in Figure 7.5. In laser-assisted traditional-HMMPs, mostly cutting processes (turning, drilling, milling and grinding) are combined with laser while electrodischarge machining (EDM), electrochemical machining (ECM), electrochemical discharge machining (ECSM) or water jet machining (WJM) are combined with laser to achieve laser-assisted nontraditional-HMMPs.

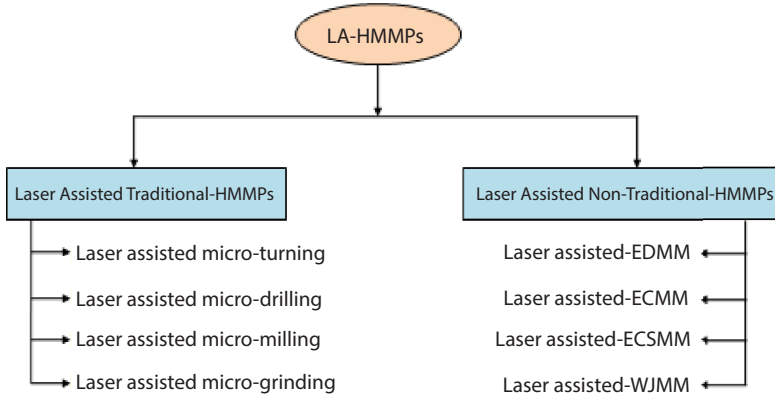

Figure 7.5 General classification of LA-HMMPs.

7.3 Laser-Assisted Traditional-HMMPs

Generally, laser light is employed for removal of material through melting and vaporization in LBM/LBMM process. However, it can be partially applied for heating and softening of materials when combined with traditional metal cutting (turning, drilling or milling) processes [15]. Here, laser energy is utilized for softening of objects while traditional processes are responsible for machining. In traditional machining, tool hardness is always greater (1.35–1.50 times) than workpiece hardness [16]. Hence, machining as well as micromachining of extremely hard materials becomes difficult for traditional processes due to excessive tool wears, poor SQ, chattering and high vibration. The application of laser in traditional machining/micromachining leads in material softening as a result reduction in tool wears, better SQ, lower vibration and chattering at low specific energy consumption. The common laser-assisted traditional-HMMPs are summarized as:

- Laser-assisted microturning process
- Laser-assisted microdrilling process
- Laser-assisted micromilling process
- Laser-assisted microgrinding process

7.3.1 Laser-Assisted Microturning Process

Laser-assisted microturning (LAMT) is utilized laser as heat source for softening of workpiece for turn cutting at macro/microscales as shown

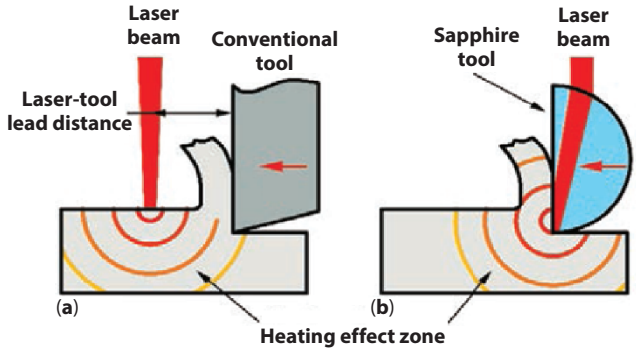

Figure 7.6 Various modes of LAMT process; (a) application of laser infront of tool; (b) application of laser through tool [17].

in Figure 7.6 (a) [17]. In simple, it can be defined as hybrid cutting process where hardness of material decreases locally and instantaneously with application of laser energy [17]. Here, rotating object is preheated infront of cutting tool by means of laser energy and soften material prior to removal of metal in form of chips without phase transformation [15, 17]. It can be employed for turn cutting of extremely hard materials like high hardness steels, tungsten carbide (WC), silicon, ceramics, composites, glass, sapphire, mold and die steels [17–20]. It effectively improves the efficiency of integrated process and quality of products. It significantly decreases in cutting forces and energy consumption than normal turn cutting [17].

Generally, laser is employed for heating of material infront of tool causes loss in heat energy due to heat transfer at actual cutting point. Hence, excessive heat is required to achieve the desired cutting efficiency. Due to extra heating means local bucking, phase change, physicochemical interactions, and thermal cracking [21]. Hence, direct application of microlaser is tested by researchers to overcome such limitations of LAMT process. Here, laser beam is directly passed through cutting tools during turning as shown in Figure 7.6 (b). For this, infrared (IR) diode laser has been integrated with diamond tool to focus at desired point on workpiece passing through diamond cutting tool.

Off course, direct application of laser enhances the machinability of turn cutting process. However, it requires microcutting tools (5μm~1mm) made of diamond [19, 22]. The high cost and difficulty in manufacturing limits the applicability of such integrated process. In this situation,

sapphire becomes an alternative of diamond tool because of their unique properties as high hardness and transmissivity. It can sustain hardness with small variations with increase in temperature and also allow laser to easily pass through it.

The performances of LAMT are always better than normal microturning in term of better SQ at low specific energy consumptions. The SQ of LAMT turned surface was found about 80% better than normal turning of silicon (Figure 7.7) [19]. The SEM images of unturned and turned surfaces (normal/laser-assisted) are presented in Figures 7.8 (a)–(c) respectively [19]. The application of laser is not always beneficial and excessive heat transfer means reduction in quality of turned surfaces. Hence, desired quantity of laser heat input is always preferred for quality turning of materials.

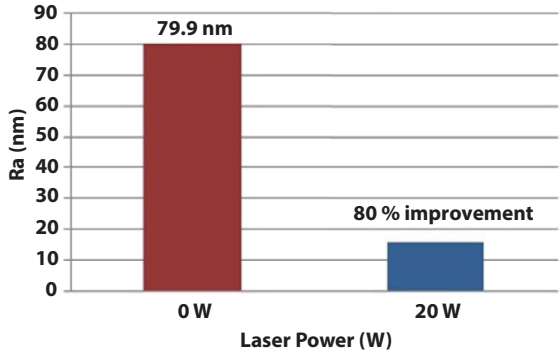

Figure 7.7 Effect of laser power on surface roughness [19].

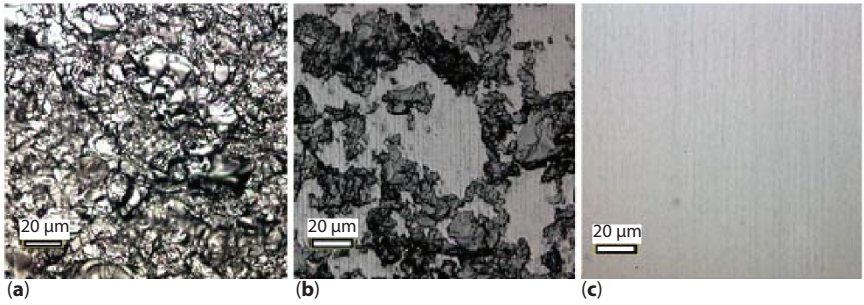

Figure 7.8 SEM images (a) unmachined surface; (b) turned surface without laser; (c) laser-assisted turned surface [19].

7.3.2 Laser-Assisted Microdrilling Process

Drilling is an important method for making holes into transmission systems of automotive at macro/microscales. Even though, it faces challenges and becomes time consuming for difficult to cut metals that limits the applicability of drilling. The process becomes more difficult for drilling of holes at micron and submicron scales with high aspect ratio into such difficult to cut metal and alloys. To overcome the problems, laser energy is employed with conventional microdrilling for softening of material. Such integrated process is known as laser-assisted microdrilling (LAMD) as schematically presented in Figure 7.9.

LAMD is one of powerful tool for making of holes at microscale with application of laser during drilling process. In this process, a tiny area is heated by laser just under tip of drill. Due to this, temperature of workpiece increases, and material becomes softer [23, 24]. Hence, drilling of softer material becomes easier because of reduction in cutting forces and resistance. It gives better performances than conventional drilling in term of higher productivity, reduction in tool wears, precise geometrical controls with significant reduction in cycle time related to machine and manpower [23–25]. The pre-heating by laser significantly reduces drilling time as 16% to 40% in different conditions for drilling of cast iron, stainless steel and alloy (C45) steel [25].

LAMD process is suitable for drilling of microholes into high hardness materials, shafts, and other similar objects. It is mostly preferred in automobile sectors for macro/microholes drilling into crank shafts, connecting rods and other transmission systems [23, 25]. Even though it suffers with several demerits, such as spike formation and softening of drill bit for drilling of high aspect ratio holes into difficult and hard metals.

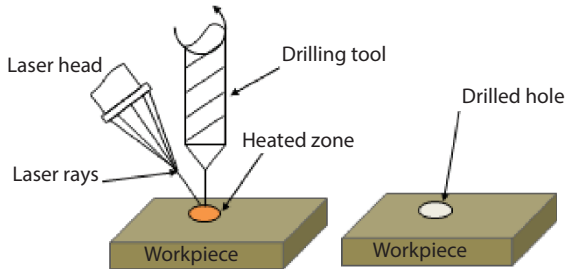

Figure 7.9 Schematic of LAMD process.

7.3.3 Laser-Assisted Micromilling Process

In traditional cutting processes, micromilling is more desirable and flexible process for manufacturing of 3D complex profiles especially for dies and mold steels with microfeatures. However, the productivity of micromilling is limited due to rapid tool wears, relatively low stiffness and bending as compared to traditional milling cutter [26–30]. Instead of this, long length to width ratio leads in probability of tool deflection and breakage in case of micromilling [29]. To handle such limitations, the laser-assisted micromilling (LAMM) becomes a promising method for 3D microstructuring.

LAMM process can be developed by combining the features of laser with micromilling process. Here, workpiece is preheated ahead milling tool by laser radiation causes of softening of material as presented in Figures 7.10 (a)–(b) positively. Due to this, enhancement in machinability of milling in term of reduction in cutting forces and higher tool life with better SQ [28, 29]. The LAMM process is suitable for creation of 3D microstructuring, microgrooves and complex geometries. It is a suitable method to manufacture complex profiles made of heat-treated alloys, nickel-based super alloys, titanium alloys, tool steel, hot and cold rolled steels especially for dies and molds with microfeatures [28–30]. It is significantly used in microgrooving, microslotting, and microchannelling of difficult to cut materials.

Off course, LAMM is a novel process for micromanufacturing but the controlling of laser radiation with tool path accordance to profile of object becomes difficult for manufacturers. The complex geometry and path programming become also necessary for laser source that makes it costly process. The smaller size of milling cutter and it manufacturing at micron level

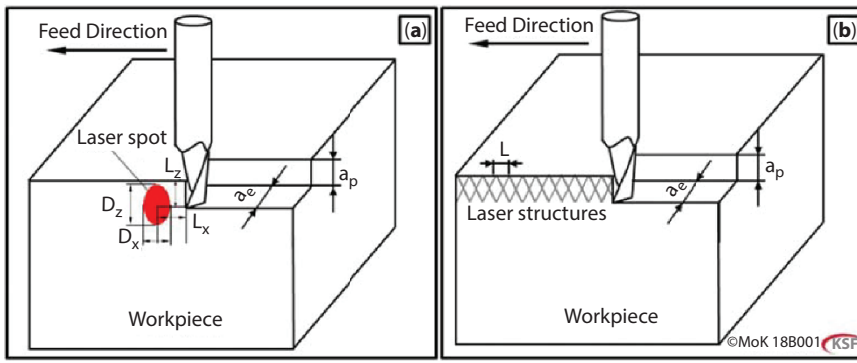

Figure 7.10 Schematic view of LAMM process; (a) softened area; (b) structures area [30].

becomes challenges for industries. Instead of this, deformation of tool due to thermal softening also limits the applicability of LAMM process.

7.3.4 Laser-Assisted Microgrinding Process

Laser-assisted microgrinding (LAMG) comprises laser features with mechanical grinding where ultra pulse laser is employed for pre-heating of object and material removal occurs by microgrinding phenomena [31, 32]. A typical schematic diagram of LAMG process and experimental setup is shown in Figure 7.11 (a)–(b), respectively [33]. The basic reason behind the development of LAMG process is to difficulties in micromachining of difficult to hard materials with high SQ by mechanical grinding process. Off course, conventional microgrinding (CMG) is the most common method for super finishing of objects at micro/nano scales, but high grinding forces causes of tool deflection and rapid wears [32]. In such conditions, the application of laser energy in CMG becomes an effective method to remove such limitations of CMG process.

In LAMG process, the thermal heating by laser means softening of material prior to grinding that assists the grinding process without melting of material and altering of microstructures. Due to this, the LAMG becomes an advantageous for microfabrication of hard and difficult to shape materials such as carbide alloy, quartz, glass, silicon nitride (Si_3N_4), aluminium oxide (Al_2O_3) and silicon carbide (SiC) [32–34]. Mostly, performance of LAMG is always better than CMG in term of lower in cutting forces and tool wears with better SQ. Instead of this, the microtip of wheel may significantly sharpen by laser during microgrinding without cracks and burr

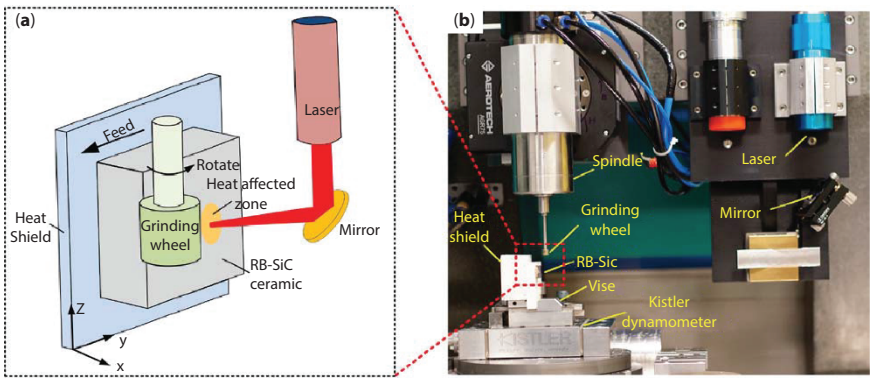

Figure 7.11 Detail of LAGM process, (a) schematic view of setup (b) experimental setup [33].

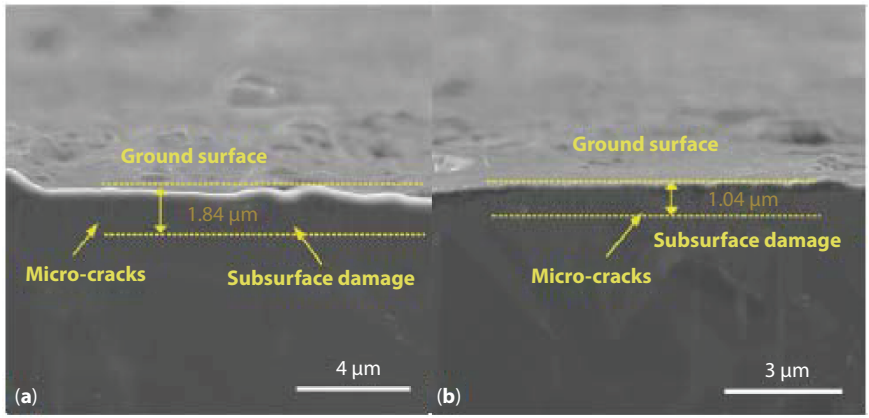

Figure 7.12 SEM of surface damages, (a) Conventional grinding (b) LAMG process [33].

formation [34]. The quality of machined surface by LAMG is much better than CMG without any subsurface damages [31].

With properly controlled parameters means significantly enhancement in the SQ and reduction in cutting forces for LAMG process. It effectively reduces the cutting forces about 40% [32] while surface roughness and subsurface damages are by 37% to 40% and 22% to 50% respectively [33]. The subsurface damage for grinding and laser-based grinding is presented in Figures 7.12 (a)–(b) [33]. It also provides deeper groves than CMG process without surface damage because of thermal softening of material [31].

The application of laser in microgrinding significantly assists the performance of grinding but simultaneously dominates the melting point of materials and bonding strength of wheel [34]. Due to thermal softening, losses of abrasives particles without wears as a result reduction in wheel life. It may also be possible that microchips easily entrapped/bonded with bond materials causes wheel loading. Even though application of laser is limited only for flat surfaces and challenging for complex and deep holes grinding. Instead of this, the initial setup cost and skill operator also limits the applicability of laser in microgrinding.

7.4 Laser-Assisted Nontraditional HMMPs

In laser-assisted nontraditional HMMPs, the laser energy is utilized to assist the advanced micromachining processes (EDM, ECM, or WJM). The common laser-assisted nontraditional HMMPs are listed as follows:

- Laser-assisted electrodischarge micromachining
- Laser-assisted electrochemical micromachining
- Laser-assisted electrochemical spark micromachining
- Laser-assisted water jet micromachining

7.4.1 Laser-Assisted Electrodischarge Micromachining

In various noncontact machining processes, EDMM (electrical discharge micromachining) broadly accepted for machining of hard and difficult to cut metals at micro/nano scales. In this process, material removal occurs due to melting and vaporization when spark is created between electrodes in presence of electrolyte [35]. It provides high quality products free from mechanical stresses because of noncontact nature of process. Instead of this, it gives less HAZ as compared to laser microprocessing of metals [36]. Even though, low machining rate and high tool wear are major limitations of EDMM process [35]. On other hand, thermal energy-based LBMM is used to create desired profiles on workpiece surface through various configurations (drilling, milling, grooving or turning) of laser. Off course, LBMM is a quick material removal process but suffers with poor SQ, tapered profiles and larger HAZ [36]. Hence, laser combined with EDMM in sequentially and referred as laser-assisted electrodischarge micromachining (LA-EDMM) process that able to overcome the limitations of constituent processes.

LA-EDMM comprises the features of LBMM and EDMM processes in a sequential manner as shown in Figure 7.13. In this process, laser (short/ultra short pulse) is utilized for pre-machining (drilling, grooving, cutting etc.) or simply say rough cutting on base material. Subsequently, EDMM process is applied to remove recast layer and HAZ formed by laser processing [36–38]. It is an effective way to finish the objects machined by

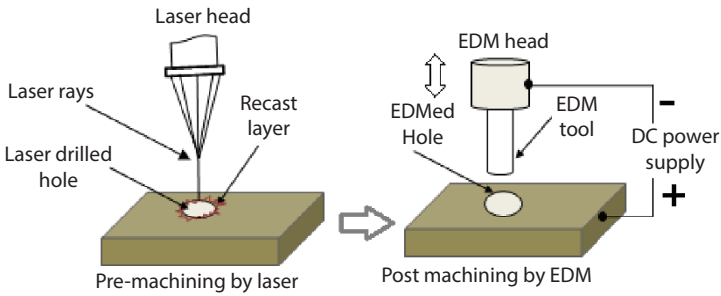

Figure 7.13 Sequential application of LBM and EDMM in LA-EDMM process.

LBM/LBMM to make them defects free with effective elimination of recast layer and HAZ. It also reduces the material processing time with quality products. Hence, low material removal limitation of EDMM process can be eliminated effectively [36, 38].

LA-EDMM process is significantly reduced the machining time about 70% [38] and 50% to 65% [37] with better quality than microholes drilled by EDMM process. The SEM images of drilled holes by EDMM and LA-EDMM processes are presented in Figures 7.14 (a)–(b) [38]. Furthermore, Figures 7.15 (a)–(c) [38] show that accuracy of LA-EDMM machined hole (approx. 140μm) is better than laser drilled hole (100μm) and EDMM drilled hole (approx. 146μm) [38]. It is applied for microdrilling into aeronautical and turbines parts like combustion casing, vanes, and blades for effective cooling [39]. It also becomes a unique method for drilling of holes of fuel injector nozzle for diesel fuel engines [38].

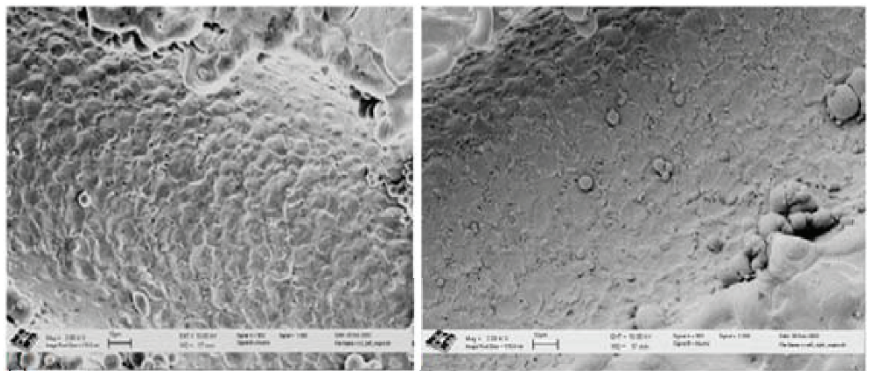

Figure 7.14 SEM images drilled holes; (a) EDMM process; (b) LA-EDMM process [38].

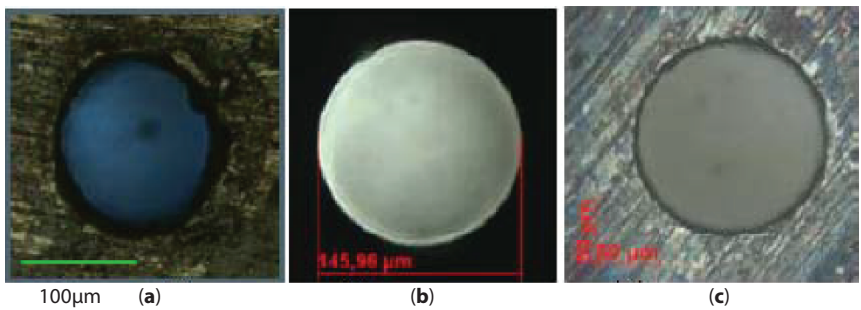

Figure 7.15 Drilled holes by different processes; (Laser pilot hole); (b) EDM drilled hole; (c) hole drilled by laser-EDMM processes [39].

LA-EDMM process has been found an appropriate method for micro-drilling and microfabrication, but it requires two separate platforms for LBMM and EDMM operations. Due to this, increase in the changeover time from one platform to another. Instead of this, the initial cost for LA-EDMM process is higher and it requires well skilled operator for laser as well as EDM process.

7.4.2 Laser-Assisted Electrochemical Micromachining

Electrochemical micromachining (ECMM) is one the most prominent method for shaping of electrically conductive materials at micron and sub-micron levels where material removal occurs by metallic dissolution in presence of electrolyte. The machined parts are highly precise and stress free [40, 41]. The high material removal capability without tool wear makes it wonderful technique for processing of difficult to shape electrically conductive materials in different profiles including complex geometry and 3D structures [40–42]. It is applied in different manufacturing areas as aerospace, automobiles, defence and medicals [40, 42]. The performance of ECMM depends on chemical dissolution and high dissolution means high machining rate. Hence, the controlling of dissolution becomes necessary for precise and efficient machining which is a difficult task. Instead of this, the stray losses surrounding tool also limits the applicability of ECMM process.

To enhance the machinability of ECMM, various approaches are tested such as minimize the IEG (inter electro gap), application of insulated electrodes, rotating tool and low voltage for machining [41]. Even though, the ionic dissolution is not shown significant improvement in most of cases. Hence, another methodology refers as hybridization of ECMM with laser that shows potential in fast and rapid dissolution of metallic workpiece. As a result higher productivity in term of material removal. Such process is known as laser-assisted-ECMM (LA-ECMM) process.

In hybridization of laser with ECMM, low-power (375–570 mw) laser energy is utilized for localized heating of electrolyte with effective application of solid (Nd:YAG or fiber) laser into IEG [40, 43]. The localised heating of electrolyte by laser leads to increase the temperature resulting higher dissolution. Hence, higher material removal can possible with precision and accuracy [40]. Here, laser radiation also helpful for removal of oxide layers formed on workpiece surface in presence of certain electrolyte. Furthermore, another combination of laser with electrochemical jet micromachining (ECJMM) is developed by researchers to enhance the performance of exiting LA-ECMM process which is known as LA-ECJMM process.

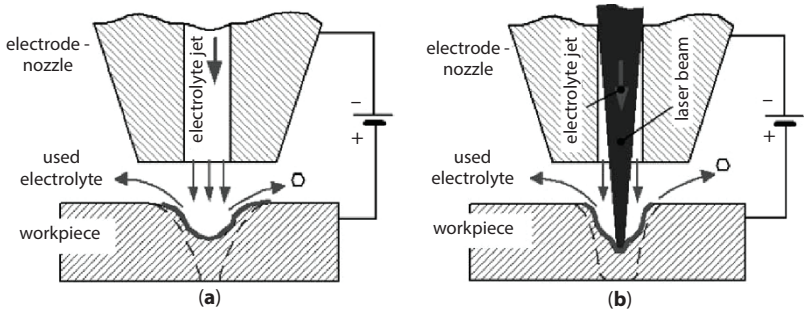

Figure 7.16 Hybridization of ECJMM and laser beam; (a) ECJMM without laser process; (b) LA-ECJM/ECJMM process [44].

LA-ECJMM comprises the laser with electrolyte jet where material removal occurs due to electrochemical dissolution [44]. The typical diagram of ECJM/ECJMM and hybridized ECJMM with laser are presented in Figures 7.16 (a)–(b). Laser energy significantly enhances the precision machining with high material removal by localized thermal heating of electrolyte resulting enhancement in electrochemical dissolution at target area. It also prevents the unwanted machining especially stray losses [40, 43–45]. The key advantage of LA-ECJMM is to accelerate the dissolution along with flushing in any desired location. On another way, the application of laser energy in ECMM/ECJMM is significantly raised the boiling nature of electrolyte and electrical discharge that adverse effects on performance of process. Generally, laser beam and electrolyte jet must be coaxially in LA-ECJMM, but the hydrodynamic behaviour of electrolyte jet disturbs the alignment in several cases. The evaluation of gases at cathode also crates disturbance and turbulence for jet of electrolyte near target area during machining of objects. However, machining of miniatures (5–500 μm) made of ceramics, composites, or alloys with high accuracy (1–10 μm) is still challenges for it [40].

7.4.3 Laser-Assisted Electrochemical Spark Micromachining

Electrochemical spark micromachining (ECSMM) is simply known as ECSM (electrochemical spark machining) that shows their ability in micromachining of ceramics materials including glass, quartz, and Pyrex [46]. In general, it is hybridization of EDM and ECM to eliminate the limitation of such processes as needs of electrically conductive metal and alloys for processing. On other hand, ECSM can be defined as a noncontact thermal energy-based method that comprises features of EDM and ECM.

Here, material removal occurs due to melting and vaporization when spark is created between tool electrode and gaseous (H_2 gas) layer with application of suitable discharge voltage in presence of electrolyte [46, 47]. It is applicable for micro/nano machining of variety of materials including ceramics and electrically nonconductive as well as conductive materials [46]. Even though, it suffers with recast layer, HAZ and microcracks due to rapid cooling [46]. In such situations, hybridization of ECSM/ECSMM with laser in sequential manner is become an effective tool to minimize the associated problems. Such combined process is referred as laser-assisted-ECSMM (LA-ECSMM) process.

Like LA-EDM, laser and ECSM processes are applied sequentially for processing of materials through LA-ECSMM. In this process, laser is applied either pre-processing or post-processing [47]. Mostly, the bottom surface microgrooves in glass ceramic consists with uneven surface, protrusion like structures, over cutting, HAZ with taper profile when processed by ECSMM. On other hand, microgrooves straight edge profile is not possible when laser is used for processing individually. Furthermore, the laser machining of microgrooves shows V-profile with larger taper and HAZ [47]. The combined effort of laser and ECSM effectively reduces the HAZ, recast layer and taper formed by either LBMM or ECSM/ECSMM processes.

In LA-ECSMM process, either laser or ECSMM are applied sequentially to improve the machinability of process. When laser is applied as post processing for shaping of bottom of microgrooves formed by ECSMM then the protrusions are significantly removed by laser, but edge quality of grooves is still poor. On other way, when ECSMM process is applied as post processing of microgrooves formed by laser machining then the grooves obtained with better edge quality with improvement in taper and V-shape profile converted into U-shape profile of microgrooves [47]. Hence, application of ECSMM for post operation after laser is better for machining of microprofiles like grooves, chute, holes or other microprocessing in/on ceramic and nonconductive materials. Even though, it requires separate platform for each process as which enhancement in processing cost.

7.4.4 Laser-Assisted Water Jet Micromachining

Laser-assisted-water jet micromachining (LA-WJMM) is a better technique for microprocessing of brittle materials (ceramics, glass and composites) without thermal damages of machined surfaces. The extremely hard metals like diamond, cubic boron nitride (CBN) and sapphire can be cut with better SQ by LA-WJMM process [48–50]. The basic objective

for combining laser and WJM (water jet machining) is to minimize the thermal damages occurs due to laser machining. Mostly, high-power beam intensity (1 MW/cm^2) is utilized for laser machining where material removal occurs by melting and vaporization causes of thermal damages [2]. On other way, less thermal energy is required for LA-WJMM process that utilizes for softening of material resulting reduction in thermal damages of test material. Such softened material is removed by expulsion of high-pressure water jet.

The typical diagram of LA-WJMM is presented in Figure 7.17 [49]. In this process, the laser and water jet moves simultaneously during material removal process. Here, low-power laser (max. 1.5 kW) is used for precise heating in a tiny area on workpiece surface as which temperature gradient zone is created equal to depth of thermal diffusion [48]. Hence, heated zone tends to expand that restrained by surroundings resulting high compressive stresses in heated zone. Subsequently, compressive nature of heated zone is changed into tensile nature due to rapid cooling by low pressure water jet resulting microcracks are formed on workpiece material [50]. Such cracks may extend and run along thickness of material depending upon fracture nature of material and tensile force [48].

In general, cracks follow the laser-water jet path along length of workpiece because the tensile stresses only generated in such location. Subsequently, the separation of material will be accomplished along

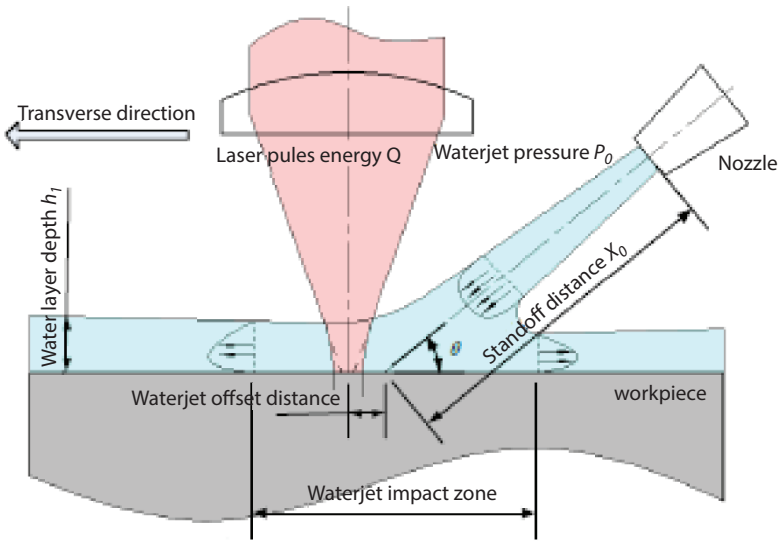

Figure 7.17 LA-WJMM process and process parameters [49].

length of workpiece through controlled propagation of cracks [48]. Due to this, material removal occurs and machined zone expected to free from residual stresses, HAZ and thermal damages. The machined surfaces are also free from visual defects because tiny debris particles are washed out by water jet.

Instead of LA-WJMM process, another combination of laser and water jet is also come in existence for microprocessing of materials where water jet is used to guide the laser beam. Such process is known as water jet guided laser (WJGL) cutting process. It is an effective way for precision cutting without burrs with less heat with pollution free cutting than tradition processes [51–55]. The basic concept of water jet in laser machining is created to replace the assist (inert) gas by water stream that broadly used in conventional laser cutting process. The WJGL process shows superior machinability than laser machining and varieties of material can be machined such as brittle and ultra-hard, heat treated and mechanically sensitive, electrically conductive/isolating materials [52–54]. The basic advantages of WJGL process are to transfer of energy into water than material and cooling of cut edges by water jet resulting less HAZ, thermal damages and thermal residual stresses [52].

Figure 7.18 shows the typical diagram of WJGL cutting process and their main components that affects the performance of process [52]. Here, laser is guided through high pressure (50–80 MPa) water jet and employed for cutting [52]. In WJGL process, the water jet is worked as optic surface

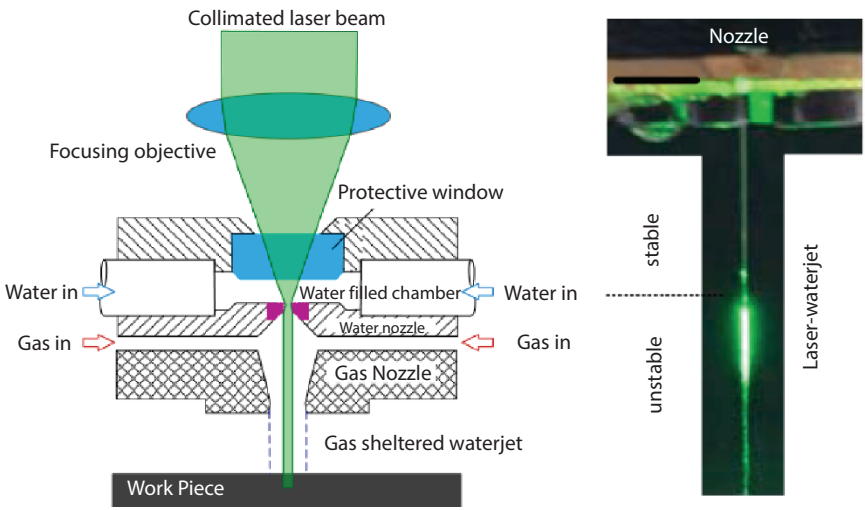

Figure 7.18 Principle of WJGL process [52].

to reflect laser at work material. A focusing lens is utilized to focus the laser into small diameter (diameter = 20–150 μm) of nozzle [51]. The nozzle is fitted beneath the chamber of de-ionized water. The laser gets reflected at interface of water and air when comes in contact of pressurized water into nozzle. Hence, ablation of laser beam occurs causes of melting and vaporization of material. On other hand, the water jet cools the target material resulting reduction in generation of harmful gases and smokes.

In WJGL cutting becomes beneficial in many ways as not requirement of focal optics because water works as optics. Here, a very small amount of mechanical force (<0.10 N) delivered by jet unlike to conventional jet machining (1–5 N) causes of scathing of material from the surface of workpiece [55]. Instead of this, the controlling of laser within the guided water is difficult that affects the precise machining and efficiency.

7.5 Capabilities and Shortfalls of LA-HMMPs

Off course, LA-HMMPs show there potential for microprocessing of difficult to cut metals. It is widely utilized in precision manufacturing and advanced industries especially aeronautical, aerospace, automobile, military, dies and molds because of high hardness and wear resistance characteristics in nature. In conventional LA-HMMPs, the localized heating of material leads in thermal softening of workpiece as which significant reduction in hardness, yield strength and strain hardening. Subsequently, thermal softening causes change the deformation nature of materials from brittle to ductile. Hence, cutting becomes easier with better SQ, reduction in cutting forces and tool wears.

In conventional LA-HMMPs, short/ultrashort lasers are applied infront of cutting tool for thermal softening of work. Here, to maintain a uniform temperature throughout cutting is difficult for turning as well as other processes. Hence, application of two-lasers becomes a novel approach but raises the initial cost and complexity. Instead of this, other issues may also be raised (local buckling, thermal cracks and phase changes) due to excessive heating [21]. To overcome the problem, the direct heating-based LAMT is a unique technique where microlaser directly applied at desired location throughout cutting tool [17]. Off course, direct heated LAMT significantly reduces the heat loss with reduction in cutting force by 9% to 15% and also reduction in surface roughness by 0.34 to 10 μm for turning of aluminium alloy [17]. Even though, difficulties in manufacturing of microtool made of diamond also limits the applicability of direct heating-based LAMT process.

LAMD is one of popular method for making through, holes, blind holes or partial holes into difficult to cut and hard materials with precise geometry in minimum possible time than drilling process. It significantly reduces the drilling time by 16% to 40% with reduction in holes diameter by 85% to 140% in different conditions of machining for chrome steel, high carbon steel and stainless steel [25]. The spike like formation and application of laser beam for high aspect hole drilling are major issues. The thermal softening of drill affects the cutting ability of tool and leads in thermal deformation of drill tools. Similarly, micromilling cutter and their manufacturing for application of laser beam in desired location is always challenges in case of LAMM process. Even though, the LAMM is applicable for 3D structuring, grooves formation, complex geometry made of heat-treated alloys, super alloys, titanium alloys, hot and cold rolled steels [29, 30].

In category of finishing processes, CMG is the broadly accepted process that applicable for hard and brittle materials. The application of laser with CMG significantly enhances the machinability with better SQ and low specific energy consumption [33]. The thermal softening of workpiece infront of grinding wheel assists in deeper grinding with high feed rate and better SQ without subsurface damages. The effective application of laser with CMG improves the surface roughness by 37% to 40% while reduction in subsurface damages by 22% to 50% than CMG process with lesser (1.5 times) processing duration for reaction bonded SiC workpiece [33]. The thermal softening also affects the bonding strength and finally loss of abrasive particles without wear at low cutting forces resulting poor wheel life. Such phenomenon increases the cost of grinding wheel. In some cases, chips particles easily entrap with softened bond material and creates wheel loading problem. Instead of this, the application of laser with CMG only limited to flat surface and not suitable for complex geometry and deep holes grinding.

The sequential application of EDMM after LBM provides better responses with better quality of machined object in term of SQ, HAZ, taper and recast layer formation. The application of LA-EDMM in microholes drilling significantly reduces the processing time about 50% to 65% without tempering of quality as compared to EDMM process [37]. In some cases, reduction in processing time upto 70% can possible with selection of appropriate parameters [38]. It is an effective method for drilling of microholes into turbine casing and aeronautical parts for cooling purposes and also drilling of fuel injector nozzle of internal combustion engines [38, 39]. Though, it requires separate platform for LBM/LBMM and EDMM that affects the overall machining time and process becomes costly.

Similar to LA-EDMM, other laser-assisted unconventional process as LA-ECMM is only applicable for micromachining of electrically conductive hard and brittle materials in presence of electrolyte. In ECMM, laser energy enhances the electrolysis process as which improvement in material removal capacity of process. Here, laser only assists the electrolysis process while machining occurs by metallic dissolution due to electrochemical reaction. It is more suitable process for 3D structuring, machining of complex profiles at micro/nano scales and applicable in aerospace, automobiles, defence, nuclear and medical industries [40, 41]. Here, controlling of electrolysis process becomes necessary for precise machining which is a difficult for manufacturing unit. In same way, the stray loss surrounding the tool also affects the quality of machined objects. To overcome the above limitations, LA-ECJMM becomes a powerful tool where laser is applied with electrolyte jet at desired location only. Hence, enhancement in electrochemical reaction of electrolysis and reduction in stray losses that prevents the unwanted stray machining [43, 44]. In some cases, hydrodynamic nature of electrolyte jet disturbs the focusing direction of laser beam as which adverse effect on machining performances. The formation of hydrogen gases also creates turbulence in jet of electrolyte near target area. Such phenomenon may also be responsible for declination of machinability performances.

Noncontact based another process refers as ECSM significantly eliminates the limitations of EDM, and ECM as needs of electrically conducive metals. The application of laser with ECSM significantly enhances the performance of LA-ECSMM process but boiling of electrolyte and uncontrolled generation of hydrogen create issues during machining. Off course, ECSM is a better machining method for microfabrication of objects made of either electrically conductive or nonconductive materials. Here, laser and ECSM/ECSMM processes are applied in sequential modes and post application of ECSM significantly provides better responses with less HAZ and recast layer.

LA-WJMM shows their potential for microprocessing of ceramic and nonconductive materials. It is an effective process for shaping of hard and brittle materials like diamond, cubic boron nitride (CBN) and sapphire without HAZ, thermal damages along with residual stress free surfaces [47–49]. In this process, the high pressure water jet necessary for removal of material from target surface but simultaneously creates disturbance for laser beam as which beam may divert from desired location. To minimize the turbulence, WJGL process shows better responses than LA-WJMM because laser heat is transmitted to water not to workpiece material. Due to this, WJGL becomes more suitable for precision machining of

brittle, ultra-hard, heat treated, electrically conductive or isolating materials [52–54]. Even though, the controlling of laser with guided water is difficult that affects the precise machining and efficiency of process.

7.6 Conclusion

Laser is a powerful source of energy that utilizes by advanced industries to meet the current demands for micromanufacturing and nanomanufacturing. In a simple way, LBMM has been suffered to fulfil the demands of industries in present scenarios with high quality miniatures. To overcome the situations, hybridization of laser energy with mechanical, chemical, or electrical energies provides a better platform for manufacturing industries. The present chapter covers the various types of HMMPs that can be developed by combining of laser energy. Here, various traditional and nontraditional processes and their hybridization with laser are discussed and explained in brief with merits, demerits, and applications. Instead of this, the capabilities and shortfalls of LA-HMMPs are discussed briefly which makes easier for readers. Overall, the present chapter provides a platform for manufacturing industries to choose a better machining process for fabrication of miniatures with application of laser-based hybrid processes. The present chapter also provides a futuristic direction for researchers to find an appropriate research field for their works related to laser-based hybrid micromachining of extremely hard and difficult to machine materials.

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